*Fast Marx Generator Development for PRS Drivers**

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ABSTRACT

Design studies for a full threat simulator to drive PRS implosions to around 50 MA in 250 ns showed the importance of Fast Marx Generators (FMG's) with intrinsic discharge times (LC)$^{1/2}$ significantly less than the present state-of-the-art in large machines (e.g. $\vee$ 500 ns in the SNL "Z"). Energy, size, complexity, and therefore cost are significantly reduced, and the need for intermediate stages of power gain are eliminated as FMG discharge time approaches an optimum (around 125 ns for 250 ns implosions) [1]. We describe designs for 175 ns and 300 ns FMGs and specific components that are being developed for use in large systems. This FMG technology development builds in part on that of systems built by the USA DoD in the 1970's and 1980's, which are also summarized. This technology can be applied to either of the fast Marxes and to the LTD described in Ref. 1 and to upgrades of existing systems such as the Z refurbishment.

Basis of Marx Requirements

The study in [1] addressed pulse power systems that drive 250 ns Z pinches intended to produce 400 kJ of krypton K-line x-rays, either a single > 50 MA module or four > 30 MA modules with separate Z pinches. Present-day Marxes with (LC)$^{1/2}$ times > 500 ns, coupled to the Z-pinch via water transfer capacitors were found compatible with single module design but could not be fitted together to drive four close-spaced Z-pinches. If the Marx (LC)$^{1/2}$ time was reduced to 300 ns, water peaking circuits could be used; the one- and four-module designs were both feasible, the single module using 96 parallel Marxes, and the water volume and intermediate switching difficulties were much reduced. Marxes with (LC)$^{1/2}$ = 175 ns could drive the Z-pinch directly without needing water, the single module now needing 256 Marxes in parallel. Marx voltages were in the 6-10 MV range. Using 200 kV pulsers in LTD stages to achieve (LC)$^{1/2}$ = 125 ns was also considered, e.g. using 448 pulsers in parallel and 45 independent sets of these in series.

Ref. 1 compares the system designs based on transfer, peaking, Marx direct drive and LTDs. Here we consider possible designs for the Marxes with (LC)$^{1/2}$ = 300 ns and 175 ns that Ref. 1 showed to be desirable. We show the relation between these and systems built by the US DoD in the 1970s and early 1980s. We describe how the earlier designs achieved performances at or beyond those now postulated even for LTDs.

Marx Designs

The capacitor designs for the (LC)$^{1/2}$ = 175 ns and the (LC)$^{1/2}$ = 300 ns Marxes are illustrated in Figure 1. Both consist of rectangular plastic-cased capacitors with two parallel bar output connectors on one 60 cm wide end face. These electrodes connect to rail spark gaps that switch one capacitor to the next adjacent stage.

The (LC)$^{1/2}$ = 175 ns Marx (Figure 1a) uses 600 nF, 100 kV (± 50 kV) capacitors 60 cm wide, 6.5 cm thick, and 50 cm long. It has approximately 94 stages when used in a 400 kJ source or 62 stages when used in a 100 kJ source.

The internal capacitor construction is illustrated in Figure 2(a). There are two sets of four 50 kV series-foil winding pads 45 cm long, connected in series at the end farther from the switch. The four 15 cm wide pads lie across the 60 cm width of the capacitor. The pad construction is very similar to that used in capacitors such as the Scyllac metal-case style and the plastic-cased capacitors in ACE-IV. The dielectric stress (energy density ~0.2 J/cc) is consistent with long-life operation, and current density levels are low.

The pads are 2.4 cm thick and are separated by 0.7 cm of high quality dielectric sheet that forms a central transmission line. The magnetic field of the current discharging the capacitor has full value in the transmission line and is assumed in inductance calculations to fall to zero on the midline of the pads. The

**Work sponsored by the Defense Threat Reduction Agency.*

0-7803-7120-8/02/$17.00 © 2002 IEEE

Report Documentation Page			*Form Approved OMB No. 0704-0188*

1. REPORT DATE **JUN 2001**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Fast Marx Generator Development for PRS Drivers**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Titan Pulse Sciences Division**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

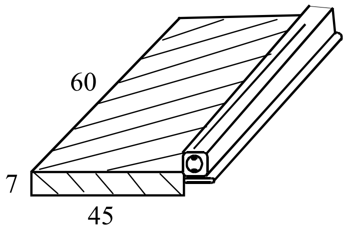
13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
Design studies for a full threat simulator to drive PRS implosions to around 50 MA in 250 ns showed the importance of Fast Marx Generators (FMGfs) with intrinsic discharge times (LC)1/2 significantly less than the present state-of-the-art in large machines (e.g. É 500 ns in the SNL "Z"). Energy, size, complexity, and therefore cost are significantly reduced, and the need for intermediate stages of power gain are eliminated as FMG discharge time approaches an optimum (around 125 ns for 250 ns implosions) [1]. We describe designs for 175 ns and 300 ns FMGs and specific components that are being developed for use in large systems. This FMG technology development builds in part on that of systems built by the USA DoD in the 1970fs and 1980fs, which are also summarized. This technology can be applied to either of the fast Marxes and to the LTD described in Ref. 1 and to upgrades of existing systems such as the Z refurbishment.

15. SUBJECT TERMS

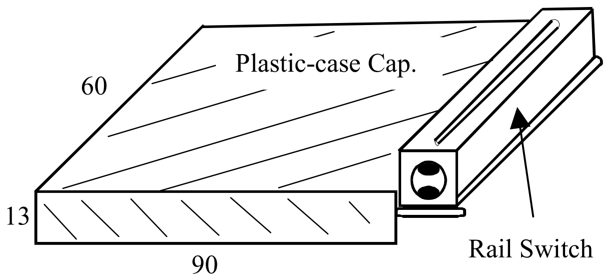
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**5**	

(a) 175 ns drive direct from 175 ns Marx



3 kJ, 100 kV, 50 nH, 600 nF

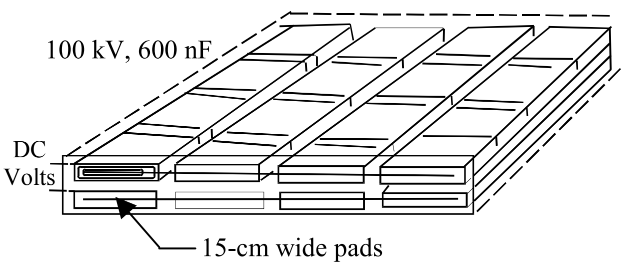
(b) 175 ns drive from 300 ns Marx using water peakers



12 kJ, 180 kV, 120 nH, 750 nF

Figure 1. Capacitor designs for $(LC)^{1/2}$ = 175 and 300 ns Marxes).

(a) $\sqrt{LC}$ = 175 ns Marx capacitor



(b) $\sqrt{LC}$ = 300 ns Marx capacitor

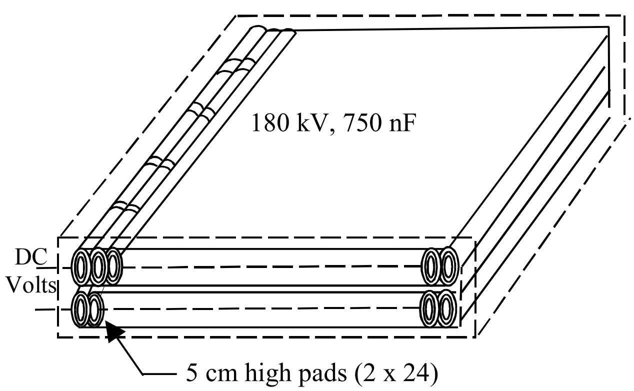


Figure 2. Internal designs of the capacitors.

capacitor inductance is calculated to be 15 nH. Assuming about four channels on average in the rail switches (as in TEMPS, see below), the 6.3 cm square section rail switch is about 10 nH. The external inductance in the oil is estimated as 10-15 nH per stage, depending on Marx length and voltage. Allowing 10 nH per stage for connections, the total inductance is 50 nH per stage or 0.5 μH/MV. With 600 nF per stage, the calculated value of $(LC)^{1/2}$ is 173 ns.

In the $(LC)^{1/2}$ = 300 ns Marx, the increased inductance allowed is used to increase the energy storage per stage two ways. First, the capacitance is increased to raise the stored charge by a factor of 2.25. Second, the stage voltage is increased to 180 kV. The higher stage voltage increases overall Marx inductance because the rail gap switch inductance increases more than linearly with voltage. The capacitance per stage becomes 0.75 μF at 180 kV.

Again 60-cm wide capacitors connect to 60-cm wide rail gaps. The gaps and capacitors are 13 cm thick and the capacitors are 90 cm long. The capacitors store 12 kJ, but are considerably smaller than ACE or Atlas capacitors.

The internal construction of the capacitor is illustrated in Figure 2(b). As in the $(LC)^{1/2}$ = 175 ns Marx, it is made from two sets of series-wound pads (± 90 kV in this case) connected in series at one end and to the external capacitor electrodes at the other. In this case there are 24 pads each 5 cm wide with their widths aligned along the 13 cm short dimension of the capacitor. This is advantageous in terms of inductance, because the distributed current in the winding flows down the 5 cm width of the foils to flow along the edge of the winding opposite the pads of opposite polarity. The magnetic field that gives rise to the capacitor inductance again has the full value in the 1.2 cm thick transmission line separating the two pad sites on the midplane of the capacitor, but falls to zero a distance into the pads equal to half their thickness. The capacitor inductance is 36 nH. The rail gap is 40 nH. The external inductance is 27-35 nH per stage depending on Marx voltage and length. The connection inductance is 12 nH for a total of 120 nH, giving with C = 750 nF $(LC)^{1/2}$ = 300 ns.

The energy density is again about 0.2 J/cc. In this design the current density at the output connection is larger, but is still well within design limits.

Previous Technology - TEMPS and PIMBS-II

The general design features of the DNA/HDL TEMPS Marx have been described in the literature [2]. The first of two TEMPS (Transportable EMP Simulator) systems was fielded in 1972. TEMPS used two 3.5 MV Marxes of opposite polarity to drive a 7 MV central switch. Each 3.5 MV Marx had thirty-five ± 50 kV stages; the layout is illustrated in Figure 3. The two 50 kV, 280 nF capacitors in series in each stage were each formed by a 35 cm wide raft of twelve 23.5 nF tubular capacitors with their terminals on each end connected in parallel. The switches were 35-cm wide square-section acrylic-body SF6 rail gaps; their midplane trigger electrodes were connected in chains to erect the Marx with a few ns jitter. The 6.3 cm-square-section rail gaps and the two 2.8 cm thick capacitors, together with plastic sheet insulation, were in a single stack with a 7.6 cm stage repeat distance. Operating in SF6 at just over ambient pressure, the 3.5 MV Marx had an inductance of about 2 μH, giving along with its 4 nF capacitance a $(LC)^{1/2}$ time of only about 90 ns. Both the observed inductance and inspection of the rail gaps suggested that these closed in a few channels on average.

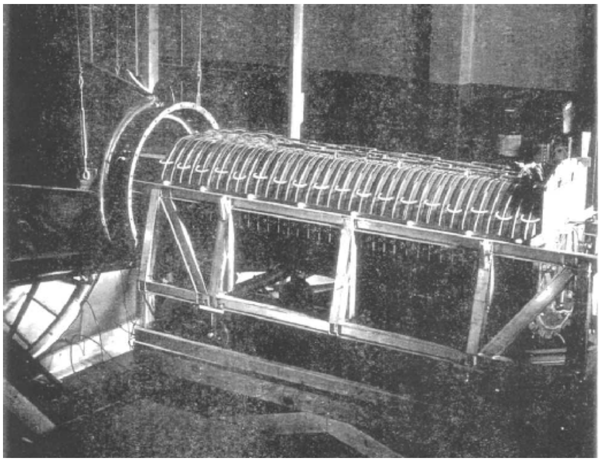


Figure 3. The TEMPS Marx.

The TEMPS Marx current was about 50 kA, and the stored charge of 14 mCb discharged without reversal in a time of about 300 ns. Switch wear was light, reliability was high, and the Marxes withstood prefire without damage. The two TEMPS system with their four Marxes operated for many years. The tubular capacitor design had the advantage that occasional capacitor failures could be remedied using one new tube rather than a whole new capacitor stage or half-stage.

The Air Force Weapons Lab-funded PIMBS systems (Physics International Bremsstrahlung Source) were initiated by two of the authors (Smith and Carboni) and completely implemented by the latter. They employed similar rafts of 23.5 nF tubular capacitors and rail gap switches in two-stage, 200 kV open-circuit pulsers, also operating in near-ambient SF6. Ref. 3 (1974), the only open publication of a PIMBS, describes the first system, two 200 kV pulsers that drive a common bremsstrahlung diode load directly through the two sides of a racetrack insulator. The parameters of each pulser are 110 nF, 33 nH, 40 mohm, $(LC)^{1/2} \sim 60$ ns.

In 1975, a two-pulser PIMBS-II test bed was demonstrated, with each pulser and rail gap capacitance increased to 190 nF using 32 tube rafts 1 m wide. The inductance of each pulser was 25 nH, giving $(LC)^{1/2} = 70$ ns. The output pulse was further reduced from ~100 ns by using a water peaking capacitor. A partly constructed pulser is shown in Figure 4.

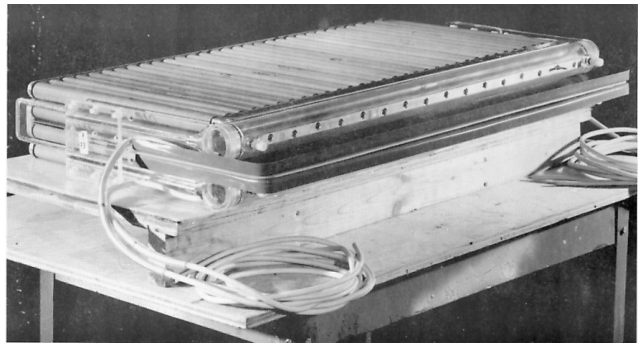


Figure 4. PIMBS-II pulser.

Four such pulsers were later combined in a PIMBS-II "module" with a common peaking capacitor, again driving a bremsstrahlung diode through the two sides of a racetrack insulator. The characteristics of this module at ± 50 kV charge were:

- 200 kV open circuit
- 125 kV diode voltage
- 1.1 MA diode current
- effective power pulse: 85 ns
- x-ray pulse: 60 ns FWHM
- stored energy: 15 kJ
- electron beam energy: 10-12 kJ

The configuration of the four-pulser PIMBS-II module is illustrated in Figure 5, and a view of the module is shown in Figure 6. A multi-plate configuration of the water peaking capacitor enabled it to be fed in parallel at four points by the four pulsers, which are arranged in pairs one behind the other. Mylar transmission lines passing between the two pulsers closest to the peaker connect the two pulsers farther away. Each of the 23 high voltage plates of the peaker has two self-closing SF6 switches, one adjacent to each side of the racetrack vacuum insulator. The effective inductance of the four pulsers including connections is 9-10 nH, and with C = 0.75 μF the system $(LC)^{1/2}$ time is 85-90 ns. However, the discharge time is decreased by use of the peaking circuit, which reduces the x-ray pulse FWHM from ~100 ns to ∧ 60 ns.

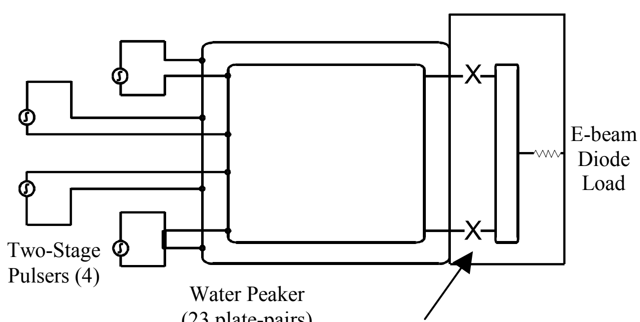


Figure 5. PIMBS-II module schematic.

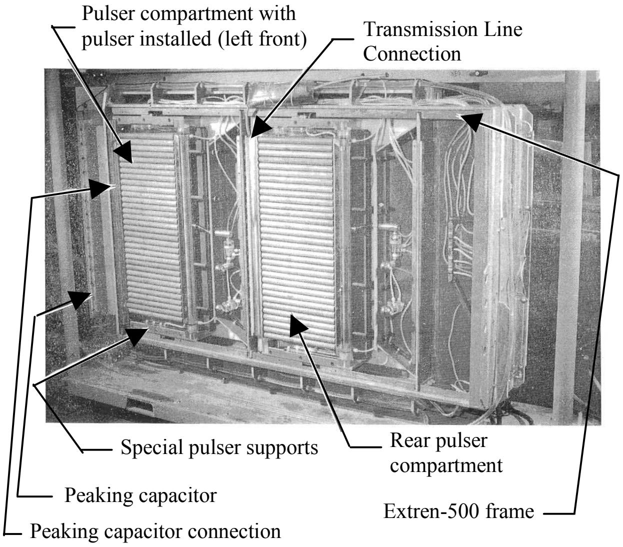


Figure 6. Partially assembled module.

In the vacuum, a tungsten anode (Fig. 7) is irradiated by up to 48 kJ of electrons from an array of parallel tungsten wires at ground potential. X-rays pass between the wires in the direction of a test object. The impedance of the diode is less than 0.1 ohms at peak power; impedance lifetime is maximized by making the anode slightly concave. The beam pinches to a line source along the center of the anode, blowing off the tungsten surface, but leaving fresh tungsten exposed for the next shot. The cathode wires and insulator surface survive to operate for many shots without maintenance.

Four such PIMBS-II modules, each comprising four pulsers, water peaker, racetrack insulator and diode, operated in parallel in a close-packed array, radiating into vacuum chambers where the test object was located. A view of the x-ray source from the diode side is shown in Figure 8; two of the four anodes are new, and the other two show wear from a small number and a large number of shots. Continuous reliable operation of this assembly of sixteen 250 kA pulsers with their low-inductance, highly stressed components proved challenging even after extensive testing and iteration, and for the 100-shot continuous operation acceptance test it was necessary to reduce the charge voltage from 100 kV to 85 kV.

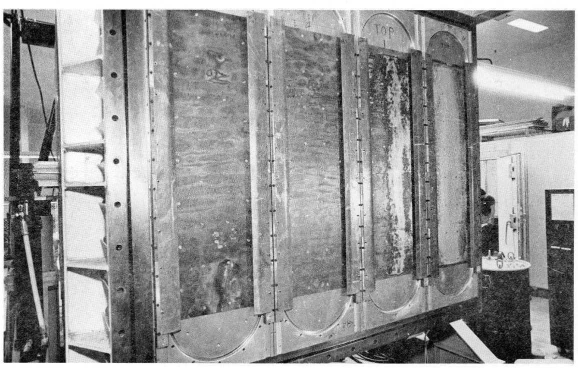


Figure 7. Diode array.

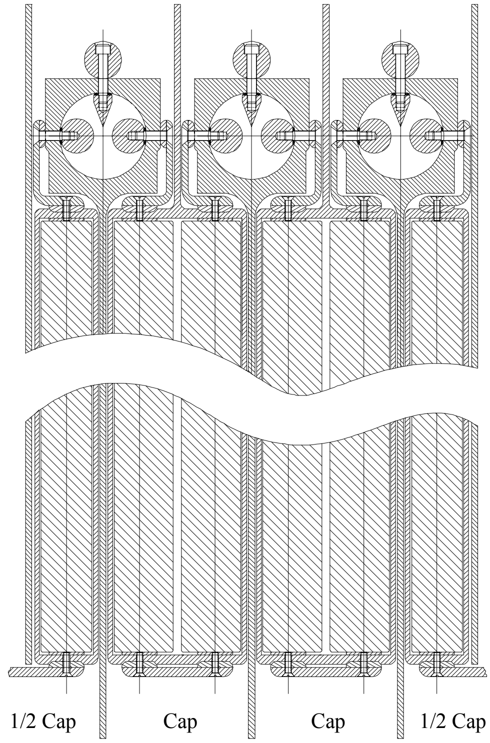


Figure 8. Conceptual cross-section of Marx stages using switch-with-barrier-approach.

The goals of the Marx generator point designs described in this paper can be compared with TEMPS Marx technology. TEMPS Marx stages were 100 kV, 140 nF, 57 nH, using 35 cm wide capacitors and rail gaps. The $(LC)^{1/2}$ = 175 ns point design uses a 60 cm width, which should make it easy to reduce the inductance to the expected 50 nH. The use of SF6-Argon mixture to increase channel number can also be helpful. The fact that the value of $(LC)^{1/2}$ in the TEMPS design is almost a factor of two lower than 175 ns is mainly what allows the capacitance to be increased to the 600 nF per stage. The charge stored is increased from 14 to 60 mCb, and the total charge transfer through the spark gaps is increased even more over that in TEMPS by post-pulse ringing. While the stored charge only slightly exceeds the values in PIMBS-II (38 mCb) where ringing did occur, it will be necessary to use a stronger switch body material, e.g. polycarbonate, to ensure switch survival in a single channel prefire. In addition, the insulating medium for both Marxes will be changed from SF6 to oil, and the voltage extended from 3.5 MV to 6-9 MV.

For the $(LC)^{1/2}$ = 300 ns design the charge stored will be increased to 135 mCb. In addition, the dc-charge voltage desired is increased from 100 kV to 180 kV with the inductance per stage increasing by a factor of 2.4; this should be possible, but a voltage closer to 100 kV could be used if the higher voltage proves to decrease reliability.

The PIMBS-II system can be regarded as equivalent to four 200 kV stages of a 1 MA LTD, each squashed flat into a racetrack geometry instead of circular, and operated in parallel without cores instead of in series. If configured with the four pulsers placed symmetrically around a central coax, without peaking capacitors, it would represent a 200 kV, 1 MA, $(LC)^{1/2}$ ~ 90 ns LTD stage storing 15 kJ. The study in Ref. 1 postulated 200 kV LTD stages storing 18-30 kJ with $(LC)^{1/2}$ = 125-150 ns achieved using up to twelve pulsers in parallel. Increasing the capacitance of PIMBS pulsers at constant inductance can give this capability with as few as four pulsers. In the case of an LTD, SF6 insulation could perhaps be continued rather than changing to oil.

Thus the PIMBS technology was well beyond that anticipated for LTDs. Based on the experience with PIMBS-II, the main challenge in such an LTD may be achieving adequate reliability in a very large number of high stress, low inductance pulsers. It is interesting to note that although the impetus to develop LTDs has been suggested to be the elimination of water energy stores, in the next generation of ~100 kV x-ray sources following PIMBS-II, the Defense Nuclear Agency adopted the successful diode technology of PIMBS but combined it with water puslelines to achieve highly reliable operation.

Marx Development Program

It was decided that development of the low inductance Marx technology should focus on the $(LC)^{1/2}$ ~300 ns design rather than the $(LC)^{1/2}$ ~175 ns design. The rationale was that the inductance per mega-volt of the two designs is similar, but the 300 ns case is more stressing because the switch is required to deal with about three times the stored charge and to operate at higher voltage. Once the larger energy 300 ns stages are developed, the technology for the faster stages is essentially developed, and they can be realized by *reducing* capacitor size and if necessary scaling *down* switch size and voltage. Therefore the goal is a $(LC)^{1/2}$ ~300 ns stage; the voltage goal set was 200 kV rather than 180 kV, and the capacitance is about 0.75 μF.

The Marx switch design will be based on the switches used in TEMPS. The TEMPS switch body had a round bore in a square cross-section that gave it added strength, by virtue of its thicker wall, to withstand prefires -- as well as providing a well-shaped building block for a linear Marx stack configuration. In contrast the PIMBS switch body had a round outer cross-section with a round bore and a relatively thin wall that occasionally broke during a prefire. With the higher charge transfer and the higher stored energy of the planned Marx, it is prudent to use the inherently stronger switch design. Additionally, stronger, more impact resistant plastics are being investigated for use in the Marx switch to assure its survival during a prefire.

The existing TEMPS design was operated reliably at 100 kV in an SF6 gas environment. The new Marx is intended to be used at up to 200kV nominal voltage with the external environment being oil. Thus, the Marx switch internal and external dimensions have been scaled up by a factor of two, as assumed in the 180 kV design discussed earlier.

Recently an experiment was performed with an old TEMPS switch body to address the voltage hold-off in oil. The TEMPS switch body held off 200 kV dc in oil without breakdown or conduction. Thus, a factor of two increase in the TEMPS dimensions may perhaps be more than adequate, for the higher voltage of the Marx.

The layout configuration of TEMPS switch bodies scaled-up to 200 kV and flat-pack capacitors having a value of about 0.75 μF at 200 kV is shown in Figure 8. The figure shows stages in which the barrier between switches is an integral part of the capacitor. Alternatively, this barrier could be a separate plastic sheet and the capacitor case could be broken up into two 100kV capacitors of half the thickness.

It is planned to test individual stages using existing capacitors to stress the switch with the desired current; to develop prototype capacitors; and to test initially a small number of Marx stages.

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[3] V. Carboni, et al., "Measurements of a Low Impedance Diode", Proc. of International Conf. in Energy Storage and Compression, Turin, 1974.